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High Transmittance Overcoat For Optimizati n of Long Focal Length Microlens Arrays In Semiconductor Color Imagers

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BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates to the optical design and microelectronic fabrication of high transmittance overcoat material(s) to increase focal length and optimize performance of long focal length microlens arrays in semiconductor color imagers.

(2) Description of Prior Art

Semiconductor array color image sensors for video cameras are conventionally comprised of complementary metal-oxide semiconductor (CMOS), charge-coupled devices (CCD), or, charge-injection devices (CID) integrated with optical structures consisting of planar arrays of microlenses, spacers, and primary color filters mutually aligned to an area array of photodiodes patterned onto a semiconductor substrate. The elementary unit of the imager is defined as a pixel, characterized as an addressable area element with intensity and chroma attributes related to the spectral signal contrast derived from the photon collection efficiency of the microlens array.

The microlens on top of each pixel focuses light rays onto the photosensitive zone of the pixel. The optical performance of semiconductor imaging arrays depends on pixel size and the geometrical optical design of the camera lens, microlenses, color filter combinations, spacers, and photodiode active area size and shape. The function of the microlens is to efficiently collect incident light falling within the acceptance cone and refract this light in an image formation process onto a focal plane at a depth defined by the planar array of photodiode elements. Significant depth of focus may be required to achieve high resolution images and superior spectral signal contrast since the typical configuration positions the microlens array at the top light collecting surface and the photosensors at the semiconductor substrate surface.

When a microlens element forms an image of an object passed by a video camera lens, the amount of radiant energy (light) collected is directly proportional to the area of the clear aperture, or entrance pupil, of the microlens. At the image falling on the photodiode active area, the illumination (energy per unit area) is inversely proportional to the image area over which the object light is spread. The aperture area is proportional to the square of the pupil diameter and the image area is proportional to the square of the image distance, or focal length. The ratio of the focal length to the clear aperture of the microlens is known in Optics as the relative aperture or f-number. The illumination in the image arriving at the plane of the photodetectors is inversely proportional to the square of the ratio of the focal length to clear aperture. An alternative description uses the definition that the numerical aperture (NA) of the lens is the reciprocal of twice the f-number. The concept of depth of focus is that there exists an acceptable range of blur (due to defocussing)

that will not adversely affect the performance of the optical system.

The depth of focus is dependent on the wavelength of light, and, falls off inversely with the square of the numerical aperture. Truncation of illuminance patterns falling outside the microlens aperture results in diffractive spreading and clipping or vignetting, producing undesirable nonuniformities and a dark ring around the image.

The limiting numerical aperture or f-stop of the imaging camera's optical system is determined by the smallest aperture element in the convolution train. Typically, the microlens will be the limiting aperture in video camera systems. Prior Art is characterized by methods and structures to maximize the microlens aperture by increasing the radius of curvature, employing lens materials with increased refractive index, or, using compound lens arrangements to extend the focal plane deeper to match the multilayer span required to image light onto the buried photodiodes at the surface of the semiconductor substrate. Light falling between photodiode elements or on insensitive outer zones of the photodiodes, known as dead zones, may cause image smear or noise. With Industry trends to increased miniaturization, smaller photodiodes are associated with decreasing manufacturing cost, and, similarly, mitigate against the extra steps of forming layers for Prior Art compound lens arrangements to gain increased focal length imaging. Since the microlens is aligned and matched in physical size to shrinking pixel sizes, larger microlens sizes are not a practical direction. Higher refractive index materials for the microlens would increase the reflection-loss at the air-microlens interface and result in decreased light collection efficiency and reduced spectral signal contrast or reduced signal-to-noise ratio. Limits to the numerical aperture value of the microlens are imposed by the inverse relationship of the depth of focus decreasing as

the square of the numerical aperture, a strong quadratic sensitivity on the numerical aperture. For these physical reasons, microlens optical design properties need to be kept within practical value-windows to achieve engineering design objectives for spectral resolution and signal-to-noise.

The design challenge for creating superior solid-state color imagers is, therefore, to optimize spectral collection efficiency by a single microlens to maximize the fill-factor of the photosensor array elements with the minimum number of microelectronic fabrication process steps. The present invention is clearly distinguished from Prior Art by introducing a high transmittance overcoat to optimize long focal length single layer microlens performance without significant optoelectronic design changes.

FIG. 1 exhibits the conventional Prior Art vertical semiconductor cross-sectional profile and optical configuration for color image formation. Microlens **1** residing on a planarization layer which serves as a spacer **2** collects a bundle of light rays from the image presented to the video camera and converges the light into focal cone **3** onto photodiode **8** after passing through color filter **4** residing on planarization layer **5**, passivation layer **6**, and metallization layer **7**. The purpose of the microlens' application in CCD and CMOS imaging devices is to increase imager sensing efficiency. **FIG.2** illustrates the geometrical optics for incident image light **9** converged by microlens element **10**, color filter **11**, into focal cone **12**, to the focal area **13** within a photoactive area **14** surrounded by a dead or non-photosensitive area **15,** wherein the sum of the areas of **14** and **15** comprise the region of the pixel.

Huang et al in U.S. Patent No. 6,001,540 teaches an optical imaging array device with two principal process embodiments to form a biconvex microlens or a converted plano-convex microlens version. In the primary embodiment, a layer of silicon dioxide is deposited onto

a substrate, followed by a deposition of polysilicon and a layer of silicon nitride. Patterning and etching the silicon nitride, a circular opening is formed and the exposed polysilicon is oxidized to form a lenticular body of silicon oxide. The surrounding silicon nitride is removed by etching to form a biconvex microlens. In the second method, a sequence of steps is employed wherein spin on glass is deposited to a thickness equal to half said lenticular body's thickness; a process is described and claimed for manufacturing a plano-convex microlens. In either embodiment, the top surface of the microlens is at an air interface with unit refractive index , n = 1.0. Control of focal length is done by adjusting the thickness of a spacer layer on which the microlens is formed.

An alternative Prior Art approach to microlens formation for solid-state image sensors is provided by Song et al in U.S. Patent 5,672,519. Song et al. teach an image sensor with a compound regular-shape microlens which extends conventional prior art from square to rectangular illuminance areas to account for CCD structures where the dimensions of a pixel or photodiode are different in the vertical and horizontal directions of the semiconductor. Song et al accomplish their extension of the prior art by two successive iterations of the conventional melt and flow process to cascade a contiguous upper lens of different curvature and/or refractive index on a first, lower lens to accommodate the dimensional mismatch of the pixel. The fabrication method consists of forming lens shapes by carrying out patterning of transparent photoresist having a refractive index of 1.6 and melting it to cause flow which, under surface tension, results in a mosaic of hemispherical convex lense array elements. Simple convex and compound convex lens classes representative of prior art are shown in **FIG.3(a), FIG.3(b).** and **FIG.3(c).**

In **FIG.3(a),** a first hemisherical microlens element **16** of a two-dimensional array of microlenses is formed in the manner described above. A successive polymer, resin, or photoresist film coating is conformally applied, photolithographically patterned, thermally reflowed and/or dry-etched. The second-layer photomask and thermal and surface tension conditions of the first microlens **16** array-plane determine the curvature and thickness of the second tandem microlens array-elements **17**.

The compound lens in **FIG.3(a)** is shown comprised of first lens **16,** second lens **17,** forming light-cone **18** converging to focal point or area **19**. **FIG.3(b)** shows a planarized first lens **20** with second lens **21** forming a compound lens converging image light-cone **22** to focal area **23**. In **FIG.3(c)** first microlens **24** is again planarized but also faceted by etching, and second lens **25** is conventionally formed to comprise the compound lens to converge image light-cone **26** to focal area **27**. Curvature control is difficult even for a single fabrication step, and, all the determinents of variance that apply to the single step apply a fortiori to the iterated process forming the compound lens. The final structure achieved by Song et al produces parallel stripes of microlenses across a base mosaic of microlenses which can be planarized to provide a flat surface for the second lens array-plane.

In all cases of the Prior Art it is observed that single simple or single compound microlens arrays, with a mapping of the single microlens, simple or compound, is to a single pixel or single photodiode sensing area in the imager. The limiting numerical aperture or f-stop of the imaging camera's optical system is that of the smallest aperture element in

the convolution train. Therefore, it is observed that the Prior Art represented in **FIGS. 3(a)** and **3(c)** have in common the further limitation of the light collection capability of the larger numerical aperture first (lower) microlens element by the addition of the second tandem microlens element (upper) which preceeds it. Spherical aberrations, coma, light scattering, numerical aperture variations, vignetting, reflective losses at interfaces, multibounce stray light, cross-talk and other optical defects described by the modulation transfer function of the upper lenses are convolved with the lower or base lenses' modulation transfer function having their own analogous set of defects. As in the case of Huang et al in U.S. Patent No. 6,001,540, Song et al share the common problem that the microlens' top surface is at an air interface of unity refractive index, $n = 1.0$, subjecting these patents to significant reflection loss at the microlens-air interface.

U.S. Patent 5,871,653 to Ling addresses high volume, low cost manufacturing methods for the mass production of microlens array substrates for flat panel display applications. In particular, it is an object of Ling to provide fabrication methods of microlens arrays on transparent substrates such as glass and polymer for sandwiching a liquid crystal within a microlens array plate. This patent does not address the problem set associated with forming integrated microlens optics for semiconductor array color imagers, and the processes, materials systems and structures taught herein are incompatible with semiconductor microelectronic fabrication sequences for semiconductor array cameras. In particular, Ling teaches three alternative methods for forming microlens arrays as curved surfaces in silicon dioxide which he terms a master mold, followed by a secondary mold with an inverted

curvature, and, completed with a third mold with the initial curvature of the master mold using conventional methods such as hot press, molding, polymerization, or casting.

SUMMARY OF THE INVENTION

Microlenses can be manufactured by a variety of different methods. The simplest method is to use standard photolithography techniques followed by melting or reflowing photoresist stripes into cylinders, or squares into hemispheres. From the equation: $F = R/(n-1)$ where F is focal length, R is radius, and n is the index of refraction, we know that we have to increase the radius R of the microlens if we want to produce a long focal length in a photoresist of essentially constant refractive index n. Experimental data has shown that we have to decrease the thickness of the photoresist film if we want to form this kind of microlens with bigger radius, associated with the surface physics and rheology of lens formation.

As the surface area of the lens increases, the volume of the lens focusing incident light on the sensing area increases. The design challenge is, therefore, how to get the most surface area of the lens and keep the focal length constrained in the available design window.

It is a principal object of the present invention to provide a manufacturable method and microelectronic fabrication process for making an ideal microlens having optimal focus performance and then overcoating at least one high transmittance film with refractive index near 1.5 on the said formed microlens to adjust the focal length within the available depth of focus design window.

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A further object of the present invention is to increase flexibility of the design and layout of semiconductor ~~array color~~ imaging devices. The present invention obviates the need for electronic or optical changes to existing ~~designs,~~and, allows compensating adaptive adjustments with minimum processing to realize design specifications.

Another object of the present invention is to improve the electro-optic sensitivity and gain value of the long focal length microlens imager, and, provide a solution for super depth focal plane CMOS, CCD, and CID image sensors. Experimental performance comparison has shown that conventional microlens imager sensitivity varies in the order of 2.5 times the pixel fill-factor, while long focal length microlens imagers average 1.8 to 1.9 times the fill-factor, where fill-factor is defined as photodiode sensing area divided by pixel area (size). The high transmittance (>95%) overcoat process of the present invention has been experimentally demonstrated to yield effective gain values for long focal length microlenses of over 2.0 times the pixel fill-factor.

Another object of the present invention is to provide an adaptive process wherein antireflection and image-forming structures, spectral color filters, and, combinations or varying configurations of semiconductor vertical profiles can be integrated with the result of maximizing collection efficiency of image intensity patterns on the photodiode planar arrays to achieve optimum pixel resolution and color signal contrast.

Another object of the present invention is to provide an overcoat process allowing the widest and most forgiving process windows for microlens and semiconductor integration

for high reproducibility, high reliability, and, consequently maximum process yield and minimum production cost.

In accordance with the objects of this invention, classes of multi-microlens optical constructs which can be combined with either conventional or novel color-filter fabrication sequences for CMOS, CCD, or CID array imaging devices are recognized. To practice the method of the present invention, conventional microelectonic fabrication techniques using photolithograhic materials, masks and etch tools are employed: in succession the array of pn-junction photodiodes is patterened with impurity dopants diffused or ion-implanted, isolated, planarized over, and, typically three more layers are built up additively with primary red, green, blue color-filters formed by the addition of suitable dyes or pigments appropriate to the desired spectral transmissivity to be associated with specified photodiode coordinate addresses in the imager matrix. Following photoresist patterning, microlens formation by thermal reflow is completed with the addition of the overcoat layer to create a high transmittance film of appropriate index of refraction over the microlens array.

Single chip color arrays typically use color filters that are aligned with individual columns of detector elements to generate a color video signal. In a typical stripe configuration, green filters are used on every other column with the intermediate columns alternatively selected for red or blue recording. Various combinations and permutations of color-filter sequences or color-filter “masks” are possible, and, a number of microprocessor

algorithms exist for balancing color components in the synthetic reconstruction of color images.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects, features and advantages of the present invention are understood within the context of the Description of the Preferred Embodiment, as set forth below. The Description of the Preferred Embodiment is understood within the context of the accompanying drawings, which form a material part of this disclosure, wherein:

FIG.1 is a simplified schematic cross-sectional profile of semiconductor and optical structures showing a typical order of elements of a conventional Pior Art device for color image formation.

FIG.2 illustrates the geometric optics factors for microlens imaging onto the photosensitive active zone within a square pixel area.

FIG.3(a), (b), (c) depicts the single compound lens configurations of Prior Art.

FIG.4 shows the precedence flow-chart of the process of the present invention.

FIG.5 is a cross-sectional view of a representative semiconductor array color imaging device, exhibiting the vertical profile in a conventional fabrication process.

FIG.6 shows the thermal reflow of photoresist for forming hemispherical microlens arrays.

FIG.7 is a representation of image formation by a short focal length microlens.

FIG.8 is a representation of image formation by a long focal length microlens.

FIG.9 contrasts the microlens' curvature of **FIG.8** when the overcoat layer is applied.

FIG.10 discloses the optical conditions for optimization of long focal length microlenses.

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DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention discloses a simple fabrication sequence and the specific optical conditions and materials properties to be satisfied in forming an overcoat of high transmittance material to optimize long focal length microlens arrays for integrated semiconductor array color imaging devices.

FIG.4 depicts the simplified fabrication flow-chart of the new process of the present invention, ordered in steps 28 through 33. In accord with the process flow chart shown in **FIG.4**, the manufacturing method of the present invention teaches formation of a long focal length microlens with an overcoat layer comprised of negative photoresist or other materials satisfying at least the following three specific conditions: (1) >95% (high) transmittance, (2) thermal resistance >270 degrees Centigrade, (3) index of refraction, n = 1.5. It is further specified that the overcoat layer thickness must be sufficient to have an essentially flat top-surface. It may also be advantageous to select the overcoat layer thickness in integral multiples of an average visible quarter-wavelength of light to satisfy antireflection coating conditions to minimize reflection loss at the air-overcoat interface where image light is incident.

The present invention further distinguishes and recognizes that the formation of a microlens array from positive photoresist renders the microlens susceptible to damage from chemical and thermal treatments inherent in microelectronic processing when formed at a surface. The present invention similarly recognizes the existence of the benefit of employing negative photoresist material for the high transmittance coating layer with

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refractive index that is closely matched at interfaces so that less light is reflected, scattered, or "lost" at layer boundaries.

FIG.5 depicts the cross-sectional view of the preferred embodiment of the present invention, showing in particular the formation of the microlens array and overcoat layer of the solid-state array imager. **FIG.5** illustrates the case of a CCD imager fabrication sequence, but it is clearly recognized that the present invention equally well applies to charge-injection device (CID) imagers and CMOS imagers. In **FIG.5**, an "n" (negative) type semiconductor substrate **34**, is photolithographically patterned by suitable photoresist coating, masking, exposing and developing, to open regions for ion-implant or diffusion doping by selected impurity atoms to form p- (weakly doped positive) type wells **35** and **36**. With similar photolithography steps, ion-implants or diffusions, an n+ type region **37** is formed to create a pn-junction photodiode and a vertical charge coupled device **38**. A highly doped positive impurity, p++, is introduced selectively to form a surface isolation layer **39**, and, a p-type well **40** is formed to isolate the CCD device **38**. To isolate pixels, a p+ channel stop **40** is formed. The gate insulator **41** is then applied over the surface of the substrate. The vertical profile is completed by processing successive additions of transmission gate **42**, interlevel insulator **43**, light-shielding layer **44**, passivation layer **45**, planarization layer **46**, microlens array-plane layer 47, and overcoat layer **48**.

FIG.6 illustrates the microlens forming process. Following the use of a standard photolithoghy step to pattern an area array of microlens preforms, **49,** heat is applied to raise the temperature of the photoresist to 160 degrees Centigrade for 10 minutes to induce thermal reflow. Resulting from surface tension, the hemispherical microlens element **51** is formed. Similarly, if the photopattern is stripes,the reflow results in forming hemi-cylindrical lenses.

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FIG.7 exhibits a color pixel image formation process by a short focal length microlens **52** onto a focal area **53** inscribed within the active region of the photodiodes. Typical for CMOS imagers, short focal lengths may be of the order of 8 microns for 0.5 to 0.8 micron feature size. For CMOS imagers with typical feature sizes of 0.25 to 0.35 microns with multiple metal levels, long focal lengths are required, as shown in **FIG. 8**. In **FIG.8,** the microlens' **54** thickness and radius of curvature are distinctly smaller than microlens **52** in **FIG.7**. The extreme light rays defined by the microlens clear aperture illustrate the focal cone half-angle comparison between the focal cones formed by the short focal length microlenses **52** and the long focal length microlens **54** converging to focal area **55**.

With the addition of the overcoat layer formed in accord with the optical and materials properties specificied in the present invention, **FIG.9** further contrasts the thickness and curvature of the microlens of **FIG.8**. In **FIG.9**, overcoat layer **56** transforms the unity refractive index, n=1.0, air-microlens interface of **FIG.8** into the index-matched, n=1.5, overcoat-microlens **57** interface. In **FIG.9**, focal area **58** resides on the plane of the

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photosensor array, and, ideally represents the median of the focal depth window.

Precise spherical surfaces are particularly easy to fabricate because the spherical shape represents a minimum in surface energy, occurring when the surface tension effect naturally forms the microlens during the photoresist melt and reflow process. **FIG.10** depicts a microlens' spherical boundary surface **59** of radius **R** centered at point **C**. In **FIG.10**, an object or point light source at an object distance **O** from the vertex **V** along the axis of the microlens will refractively converge a cone of light rays to an image at image distance **I** from point **V**. It the index of refraction in the space between the object light source is **N1** and the index in the space inside the lens (to the right of the spherical lens surface in **FIG.10**) is **N2**, then spherical wavefronts will converge to a real image at **I.** Using the well-known Fermat's Principle, it can be shown that for spherical refracting surfaces:

$$\mathbf{N1/O + N2/I = (N2 - N1)/R}$$

and, that when **O** is very large, the image focal length is then given by: **Fi = R (N2/N2-N1)**. Thus, if we can make the index of refraction **N1** of the overcoat layer approach a close match to the microlens index of refraction **N2**, the value in the denominator **(N2-N1)** gets very small, and, for fixed radius of curvature **R** of the microlens, the focal length **Fi** becomes long. In this manner, the overcoat layer material can be adjusted to optimize the microlens performance. Since depth of focus will shrink as the square of the numerical aperture of the microlens, the overcoat layer can adjust the balance to practical values of the numerical aperture to contain the depth of focus to within the designer's window for

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color-gain balance, spectral resolution, signal contrast or signal-to-noise ratio specifications. The overcoat layer provides, therefore, an analog means to avoid electronic signal processing circuit or amplifier redesign, and, provides latitude in engineering design margins. Relief of thickness process control for microlens fabrication is afforded by the easier, more precise control of the overcoat layer. Since the microlens is fabricated over many process layers, including planarization and spacers, tolerances which sum up during the process can be compensated by the overcoat layer thickness adjustment to minimize rework or loss, and, maximize final process yield in semiconductor color image cameras.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made without departing from the spirit and scope of the invention.

What is claimed is: